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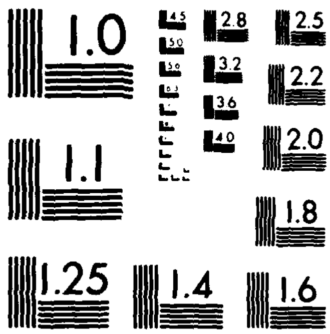

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AN OVERVIEW OF REACTOR CONCEPTS, A SURVEY OF REACTOR DESIGNS

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February 1985

Final Report

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AIR FORCE WEAPONS LABORATORY
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Nuclear reactors have been a reliable energy source for many years. Commercial nuclear power plants have an unparalleled safety record. In fact, no power plants of conventional nature such as coal, petroleum, or hydroelectric have a better safety record. Nuclear plants are virtually pollution-free. But perhaps their biggest attractive feature is fuel economy. Only a hydroelectric power plant has a clear cut lead on fuel cost, but they are restricted geographically to sufficient waterways that support them. These reasons, and many more, make nuclear reactors technically attractive as an energy source.

It is the purpose of this paper to summarize some basic reactor physics along with a simple description of different reactor types and their designs. This will yield some insight as to the technology and feasibility of nuclear reactors as power generators without imposing too much technical detail. When the facts are weighed against preconceived notions, nuclear energy is seen in a more favorable perspective.

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OVERVIEW OF NUCLEAR REACTOR CONCEPTS

A nuclear reactor, simply stated, is a configuration of fertile and fissile material arranged in such a way as to sustain a nuclear chain reaction. A fertile material is an isotope which will fission upon absorbing a neutron having kinetic energy (KE) greater than a specific threshold energy. Fissile materials are isotopes that can fission upon absorption of a neutron having any KE. An isotope is a form of an element having similar chemical properties with the same atomic number but a different atomic weight. An example of a fertile material is U^{238}. The U^{238} will fission only with neutrons having a high KE said to be in the fast energy spectrum (Ref. 1).

Classifying a neutron as a fast neutron means that it has higher KE than a neutron that has been slowed down by colliding with atomic nuclei. Each collision causes the neutron to lose some of its KE. Because KE can be expressed in the mathematical formula as $KE = 0.5\ mV^2$ where m is the rest mass of the neutron (1.675×10^{-21} kg) and V is the neutron's velocity (speed), the words speed and energy can refer to the neutron's KE. For example, a neutron having a KE 0.025 eV or 4.0255×10^{-21} J will have a speed of about 2200 m/s or $V = \sqrt{2KE/m}$. A neutron with this speed is classified as a thermal neutron because it is in thermal equilibrium with neighboring atoms. They are important because of their interaction probability with U^{235} causing a fission.

Fission occurs when a nucleus absorbs a neutron. This excites the nucleus and may cause it to divide into lighter weight isotopes called fission fragments. The KE of the fission fragments appears as heat, and radiation is produced in the forms of α, β, γ, X rays and neutrons. Between 2 and 3 neutrons on the average are born during this event. At a neutron's birth, it is in a relatively high energy state and is called a fast neutron. The neutron can lose KE by scattering with nuclei; it can leak out of the reactor, or it can be absorbed by a nucleus. Absorption and leakage will take it out of the chain reaction. The neutron could also be absorbed by a fertile or fissile nucleus and cause a fission event. Intuitively, at least one neutron must survive to cause a fission event for a chain reaction to continue.

The U^{235} is a fissile isotope. Other fissile isotopes are U^{233}, Pu^{239}, and Pu^{241}. The U^{235} is of particular interest because it has its greatest

probability of fissioning upon absorption of a thermalized neutron. Thermalizing a neutron is a relatively easy process achieved by placing a material with a low absorption probability and a high scattering probability in the neutron's path. Each scattering event will lower the neutron's KE until it has reached a thermalized energy. This process is called moderation. Most commercial power reactors utilize the concept of a thermalized neutron, U^{235} reaction which induces fission. Materials with a low mass number are the best moderators. Hydrogen, lithium, and carbon are good moderators because they have a low mass number and a low absorption probability such that scattering is the most likely interaction between the nuclei and an incident neutron. Hydrogen is especially important because it is abundant and cheap through its existence in H_2O.

Hydrogen, while primarily a moderator, can absorb neutrons. Deuterium (D_2O) or heavy water has a much lower absorption probability, and it is used in reactors using lower enriched U^{235}. However, although D_2O absorbs fewer neutrons than H_2O, it is not as good at scattering neutrons. This makes D_2O less effective as a moderator, which means more D_2O is needed to achieve the same moderating effect as H_2O. Deuterium is much more expensive than H_2O because it is much harder to obtain. However, D_2O allows the use of natural uranium as a nuclear reactor fuel. Carbon is another good moderator. Carbon is extensively used in gas-cooled reactors, but it has a tendency to oxidize at high temperatures in water-cooled reactors (Ref. 2) and may react exothermically with H_2O under certain conditions.

Moderators can also serve as reflectors. A reflector is a material that has a low absorption probability but a high scattering probability so that it tends to scatter neutrons back into the reactor core when they are attempting to leak out of the reactor. A reflector need not be a moderator, but reflectors and moderators have very similar characteristics and often a material can serve both functions.

Because of the high temperatures generated by nuclear reactors, coolants must be used to ensure material components are not subject to failure due to the temperature exceeding melting points. Also, the coolant extracts heat from the core to supply the energy for power production. Some coolants have characteristics both of a moderator and reflector. In fact, this is the case if water is used as a coolant because of the hydrogen in the water.

Water is so good at attenuating neutrons, it actually makes a good neutron shield. Concrete is another good neutron shield mainly because of its high hydrogen content. Boron has a high neutron absorption probability over a relatively large energy range. This makes boron an excellent shield. To add strength, boron and carbon are combined in the form of boron carbide (B_4C). Lithium hydride (LiH_4) is a neutron shield which is lightweight, and it can be used where shield weight is a major constraint.

Neutrons are quite different from other forms of radiation, and are very penetrating. Alpha particles are just helium (He) nuclei without orbiting electrons. Because of their electric charge (double positive), they can be easily stopped. Thus they have very little penetrating power. Alpha particles do not penetrate the outer layer of the human skin; therefore, they pose no real danger to humans unless they are ingested or inhaled into the body where they may work their way into the blood stream causing adverse effects in bone marrow. Beta particles are electrons ejected from their orbits by an excited nucleus, or a nucleus with excess energy in it. X rays are the result of orbital electrons changing energy levels or free electrons providing bremsstrahlung (braking radiation) when interfacing with atoms through their electric fields. However, the most damaging and penetrating radiations are neutrons and γ rays. If γ rays are attenuated, then α, β, and X rays are also stopped, because they do not carry a positive or negative charge. Therefore, the main concern for shielding is stopping γ rays and neutrons.

Shielding against these two radiations is complicated by the way each interacts with matter. Gamma rays interact primarily with an atom's orbiting electrons, while neutrons interact primarily with an atom's nucleus. This means more dense materials are better gamma attenuators because of their higher atom densities while neutrons are best stopped by lightweight materials. Materials such as lead, natural uranium, iron, and tungsten are good gamma shields. A combination of materials is usually considered in shielding nuclear reactors.

Shielding is not only paramount to ensure human safety, but it is also necessary to protect electronic hardware. Bipolar devices are primarily sensitive to total dose while metal oxide semiconductor field effect transistors (MOSFETS) are also sensitive. Complex circuits will usually have a mixture of

these semiconductor types, which means the shield must be tailored to dose constraints imposed by many factors.

Gamma rays are usually shielded first in a multilayered shield design. One reason for this is that the heat generated from the core is damaging to the materials used for neutron attenuation. For example, a nuclear reactor can generate enough heat to dry out concrete. The loss of water in the concrete means a loss of hydrogen's neutron attenuating effect. Also, hydrogen tends to disassociate at high temperatures; materials with hydrogen content must be treated with great care in shield design.

The reactor core is composed of various materials. The primary one is the reactor fuel. For thermal or moderated reactors, the primary fuel is U^{235}. Natural uranium is only 0.711 percent U^{235}. Reactors that use deuterium (heavy water) as a coolant can use natural uranium as a fuel. The Canadian reactor, CANDU, utilizes this concept. However, most nuclear reactors need enriched U^{235}. One method of enrichment is combining uranium and fluoride (UF_6), a gas that is passed through a porous material that allows easier passage of the U^{235} isotope than the U^{238} isotope. By going through a number of stages, a certain enrichment can be obtained. This method is called gaseous diffusion. Other enrichment processes exist or are being developed at the present time. Enrichment is very expensive; however, it usually leads to better overall fuel economy in nuclear reactors.

After the fuel is enriched, it is fabricated to a specific size and geometry, making it usable for different types of reactors. For example, there are reactors that produce isotopes for medical purposes; some reactors are used for research, and others are used for power production. Each reactor type may use a different fuel enrichment and geometric fuel form requiring different fabrication processes.

The fuel itself is usually not able to stand high reactor temperatures. The fuel can be alloyed for added strength, and a protective sleeve or cladding can be placed around the fuel to ensure fuel integrity in a radiation--high temperature environment. Zirconium and its alloys are used as cladding with water coolant because they resist corrosion (Ref. 1). Carbon in the form of graphite is widely used as cladding in gas-cooled reactors.

NUCLEAR REACTOR DESIGNS

Reactors are often classified by the way the core is cooled. Pressurized water reactors (PWRs) are moderated and cooled by pressurized water. Pressurizing the water retards boiling and allows a higher exit temperature for the liquid coolant. The coolant is usually pumped into the reactor core through the bottom to the top. The heat is transferred from the fuel to the coolant as it passes through the core. It is then channeled to a heat exchanger which collects the heat from the coolant. The coolant is then channeled to the bottom of the core where it is recirculated. This coolant loop is called the primary coolant loop. Another water loop called the secondary loop passes into the heat exchanger and water is heated and allowed to boil. (The secondary coolant loop is not under pressure.) The steam is expanded through a turbine to turn the shaft of an electric generator producing electricity. The steam is then sent through a condenser which returns the steam to its liquid state. The water is then pumped back to the steam generator/heat exchanger to complete the secondary loop. It is interesting to note that the secondary loop, which is directly responsible for the production of electricity, is never in contact with the radioactive core and; therefore, it is not radioactive.

The fuel for PWRs is usually uranium oxide (UO_2) pellets stacked in a tube that serves as cladding. Typical commercial power PWRs use fuel enriched to about 3 percent U^{235}. Fabricating the UO_2 gives the fuel important physical properaties of corrosion resistance in water, resistance to damage due to radiation, and low neutron absorption probability (Ref. 1) (other than the U^{235} component where absorption is necessary for fission).

Fuel rods are made when the cladding tubes are filled with UO_2. The fuel rods are arranged in the core in certain geometric arrays that enhance the nuclear chain reaction as well as ensure control of the core. Primary control is obtained by putting control rods in specific positions in the array. A control rod is made of a material like boron or cadmium which absorbs neutrons, taking them out of the chain reaction process (Ref. 2). Boron carbide is a common absorber used for control rods. Control rods can be partially inserted to ensure the power level. If for any reason the reactor needs to be shut down, the control rods can be dropped into the core until they are fully inserted; this condition is called a scram.

Chemical shim is the control mechanism used in most PWRs. This is a process whereby a neutron absorbing substance is dissolved into the coolant. Boric acid is an example of a soluble neutron absorber that is used in chemical shim. Chemical shim is a slower method of control than control rods, but it is a very good way to control slow oscillation in reactivity (Ref. 1). It also allows for a more uniform power generation throughout the core. Almost all reactors have a natural control device called the negative temperature coefficient of reactivity. As the name implies, when the temperature goes within a certain range in the reactor fuel, the probability of a fission declines significantly causing less to occur. Typical PWRs have a negative temperature coefficient which greatly enhances safety and control of the reactor (Ref. 3).

Criticality of the PWR reactor can be determined by these control mechanisms. A reactor is said to be critical when the ratio of the number of neutrons in a generation to the number of neutrons in the preceeding generation is equal to one. If this ratio is greater than one, the reactor is supercritical. If it is less than one, the reactor is subcritical and the chain reaction will not sustain itself. This ratio is called the multiplication factor, k. By introducing control mechanisms (control rods, chemical shim, etc.), the multiplication factor and, thus, the criticality of the reactor at any particular time can be manipulated.

PWRs have some disadvantages. Because they are operated under pressure, they must have an extremely thick and heavy pressure vessel, which is costly. Also, refueling requires that the entire head of the vessel be removed (Ref. 1). This increases the cost of refueling in terms of shutdown time. However, the advantages of PWRs are significant. They are safe and their physical parameters are well known and proven. PWRs are versatile in that they can use heavy water (D_2O) as coolant which makes natural uranium a possible fuel, as well as light water (H_2O) coolant with enriched fuel. PWR technology is available and credible for different functional sizes ranging from big power plant production to small compact cores used in Navy ships and submarines. PWRs are the most widely used reactors in the United States.

Another reactor type is the high temperature gas-cooled reactor (HTGR). As its name implies, this reactor uses gas as the primary coolant. The coolant has a higher exit temperature when leaving the core than the PWR water

coolant. This implies that better heat transfer may be obtained in the heat exchanger. However, this implication is offset some by the fact that gas molecules are spaced further apart and, therefore, do not transfer heat as easily as molecules of a liquid coolant. Also, gases are not good moderators. In fact, some gases react with neutrons so little that the reaction is negligible.

One such gas is helium. Carbon dioxide has been used in reactors in Europe, but helium is now being used more in both the United States and Europe. Helium is almost totally invisible to neutrons. About 0.0013 percent of helium has a neutron-proton reaction (Ref. 1). Helium allows the reactor to achieve a high outlet temperature.

Getting a higher outlet temperature increases cycle efficiencies. There may be no limitation to the maximum outlet temperature imposed by the gas coolant. However, constraints do exist, and they are set due to metallurgical properties of reactor component materials. Therefore, the outlet temperatures must be controlled.

Ceramic fuels like uranium carbide are best for performance in a very hot environment. The fuel cladding is commonly graphite. Graphite is widely used as a reflector and moderator in HTGRs. Graphite maintains its integrity when exposed to temperatures in excess of 2000°C (3,632°F) (Ref. 1).

The materials used in HTGRs differ from materials used in PWRs because of the higher temperatures produced in HTGRs, but they operate basically the same. Fissions take place in the reactor core. Coolant is usually pumped from the bottom of the core to the top, removing some of the reactor core's heat. The gas is then circulated to a steam generator where the gas passes some of the heat it absorbed from the core to the water that also flows through the steam generator. The gas is then returned to the bottom of the core, completing the primary coolant loop.

The secondary loop is much like the PWR secondary loop. The heat exchanger passes heat to water which is allowed to boil. The steam is expanded through turbine blades which turn the electric generator. The steam is then condensed to water and pumped to the heat exchanger to complete the cycle of the secondary loop. Figure 1 shows a simple diagram of the primary and secondary loops of both the PWR and HTGR reactor concepts. Although the

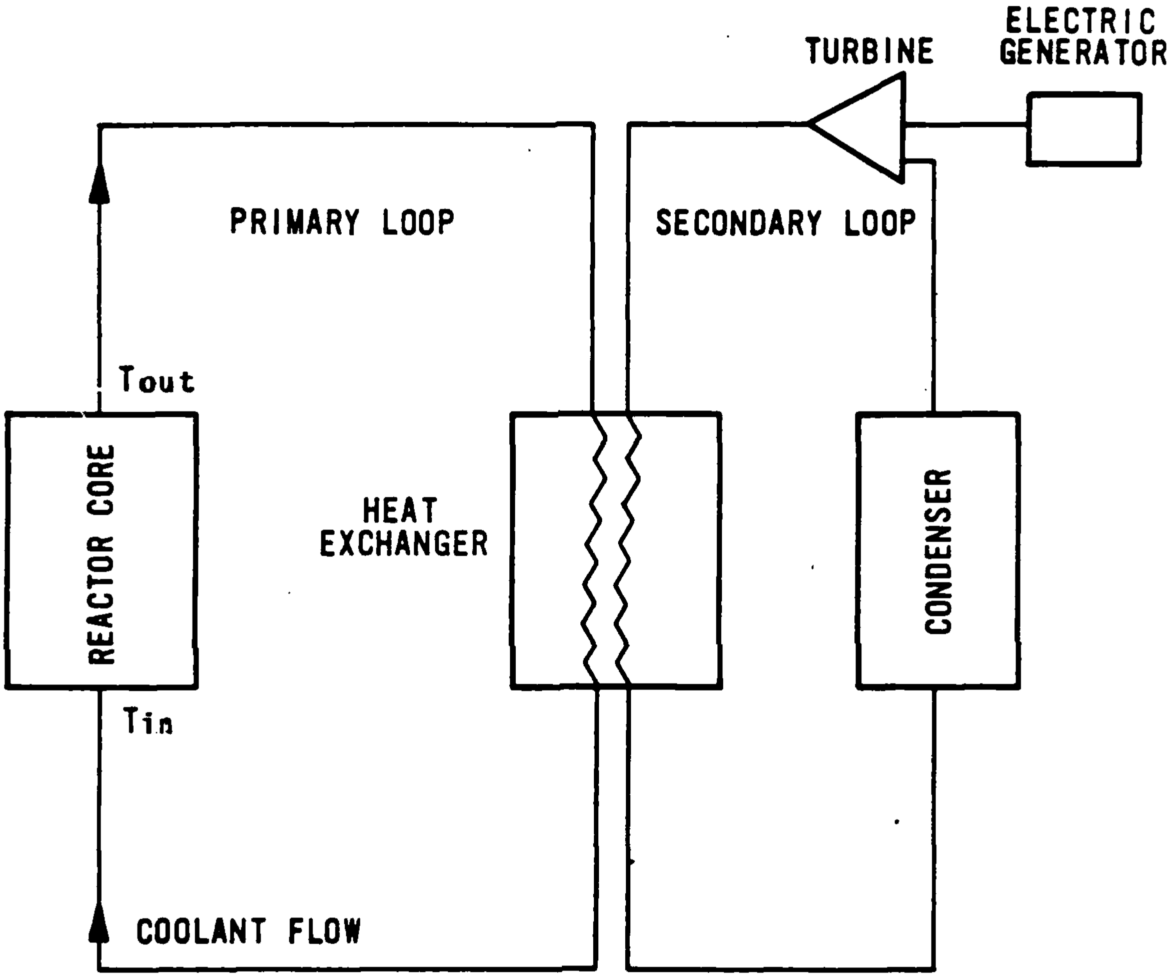

Figure 1. Primary and secondary loops in PWRs and HTGRs.

method of extracting heat for power production and heat extraction is similar for HTGRs and PWRs, their respective cores may be very different. HTGRs may use highly enriched uranium, thereby yielding better fuel economy and a reduction of the actual core size for a specific power level. The HTGR core may have fuel and control rods placed in graphite arrays similar to PWR core configuration, or they may have fuel integrated into graphite spheres and placed in the core. Such an arrangement is called a pebble bed core. HTGRs are sometimes controlled by the amount of coolant flowing through the core with control rods used only at a time when the reactor needs to be shut down.

A Peach Bottom core design is employed in some small HTGRs. The Peach Bottom core distinguishes itself by its unique fuel pin design. The fuel pin actually traps a substantial part of the fission products (Ref. 2). It does this by allowing a small amount of coolant (helium gas) to enter the fuel pin. As the fission process causes fission products to build up in the fuel pin, the fission products that do not vaporize stay in the pin while the volatile fission products are mixed with the small amount of coolant called the purge gas and are directed to an internal trap at the bottom of the fuel element. The less volatile fission products then condense and stay in the trap. The higher volatile gases are carried by the purge gas to an external trap that is located outside the fuel pin. The halogens (nonmetallic chemical elements of flourine, bromine astatine, and iodine) are removed by filtering through a charcoal bed. The other impurities are removed from the helium in the liquid nitrogen cooled traps. The purged gas is then returned to the helium coolant in the primary coolant loop (Ref. 1).

Besides having the ability to extract and contain certain fission products, the Peach Bottom fuel pins are characterized by having reflectors in the top and bottom. Graphite is used as the cladding, moderator, and reflector. The fuel is composed of highly enriched uranium carbide arranged in a matrix with graphite support inside the fuel pin. The fuel pins themselves are arranged in arrays with control rods of B_4C bearing graphite occupying specific lattice positions (Ref. 1). The main bulk of the coolant flows between the fuel pins except for the small amount that enters the fuel pins and becomes the purge gas. The inlet temperature of the coolant is about 634°C and the coolant outlet temperature is about 1354°C. The large difference between the inlet and outlet temperatures of the coolant gas makes HTGRs very attractive.

A very unique helium-cooled reactor is the German Arbeitsgemeinschaft Versuchsreaktor (AVR). The AVR features the capability of refueling while in continuous operation. Its fuel is different than previously mentioned reactor types in that it consists of spherical fuel elements, not fuel pins. The fuel elements are made of a grahite cladded with inserts of uranium carbide. The graphite coating acts as both a moderator and clad. The uranium is about 20 percent enriched U^{235}. However, the AVR has used highly enriched U^{235} and it demonstrates the ability to function with highly enriched fuel. The fuel is loaded into the reactor core at the top and discharged at the bottom while the reactor is in operation. The discharged fuel can then be inspected to see if it can be used again. The burned-up fuel spheres are replaced with new spheres and the fuel is loaded into the core.

The core contains about 100,000 graphite fuel spheres. The core is cylindrically shaped with a diameter of about 12 ft and a height of about 14 ft. The core is cooled by helium gas flowing from the bottom of the core to the top between the fuel spheres. This yields a very high outlet temperature. In fact, since 1974, the AVR has achieved the highest outlet coolant temperature of any nuclear reactor of 950°C (1742°F). This greatly enhances the heat exchange efficiency (Ref. 1).

Another attractive feature of the AVR is its negative temperature coefficient. It is larger than most nuclear reactors because of the near homogeneity of the fuel and moderator. This implies that by regulating the coolant flow, the reactivity and power level of the reactor can be controlled. This is the case except for four control rods which are used for regulation of slow reactivity changes and reactor shutdown. The negative temperature coefficient is so dominant in the AVR that if all control rods are pulled out and the helium flow stopped, the reactor will shut down. This event was tested and the core temperatures did not exceed 1200-1250°C (2192-2282°F) (Ref. 1). The fuel pellets maintained their integrity since they are designed to withstand temperatures up to about 1500°C (2732°F) with minimal loss of fission products.

Because there may be a slight loss of fission products from the fuel, the reactor vessel is designed to contain the core. The vessel also contains the steam generating system which is placed above the core. It is conceivable that a rupture in a boiler tube could cause water to leak into the core from

the top. If this happened, a water-graphite reaction could occur, especially at high reactor temperatures, causing the graphite coating on the fuel to combine with the oxygen in the water forming carbon monoxide or carbon dioxide (Ref. 4). This would expose the uranium carbide inserts and release fission products that have been trapped inside the spheres into the coolant. Also, water entering the core would vaporize, increasing the pressure inside the vessel to its rupture point.

The AVR has built-in safeguards to prevent this. The steam generator is divided into four sections. Loss of water from any of these sections would not raise the pressure inside the vessel to its rupture point, thus ensuring the safety of the reactor.

Deep basing is a term used to describe putting a nuclear reactor system underground. Underground reactors are attractive because they are less vulnerable to a terrorist or foreign attack. However, there are problems involved with underground reactor systems. Construction alone introduces problems. The reactor may have to be constructed in sections, and these sections assembled underground. Heat rejection is a problem. Conventional PWRs utilize a cooling tower to reject excess heat not collected by the heat exchanger. Deep based PWRs may not be able to do this. Because of space constraints, personnel exposure must be addressed. All of these problems are solvable with extra cost. However, when considered against the added security of an underground power system, the extra cost may be worth it.

A deep based high temperature gas-cooled reactor (DBHTGR) may be feasible. It could be a Peach Bottom core design or an AVR type. PWRs can also be considered for deep basing, but require a relatively large area. PWR technology is well known and proven in this country. This makes PWR deep basing a prime candidate for an underground reactor system.

A modified PWR may have some advantages over the conventional PWR system. One such reactor system is called the consolidated nuclear steam generator (CNSG). The CNSG is a PWR with a steam generating system (the heat exchanger, secondary loop, etc). Inside the pressure vessel, the reactor core is at the bottom of the vessel, and the steam generating system is on top. In this respect, it is much like the AVR. There is enough shielding and separation between the core and the steam generator so that the steam producing the electricity is, at most, only slightly radioactive. Because of the CNSG's

design, natural circulation from hot water rising and cooler water sinking eliminates the use of some pumps needed in conventional PWRs. With the steam generator and reactor core in the same vessel, there is a large supply of water locally available for cooling in the event that cooling problems develop. This also eliminates the need for long pipes used in conventional PWRs to carry water to an external heat exchanger which could conceivably rupture causing coolant loss which might expose some of the core. This design also allows better turbine efficiency since there can be some superheated steam

The CSNG has some significant disadvantages. It takes longer to construct an integrated system like this. Maintenance is a problem because the vessel would need to be opened to repair parts of the steam generating system. Only one reactor of this type has ever been built; it powers the German ship, *Otto Hahn*. This indicates that the CNSG's reliability has not yet been demonstrated like the conventional PWRs.

A different reactor concept is the Training-Research-Isotope-General Atomic (TRIGA) reactor. It was first conceived in 1957, and many TRIGA-type reactors are used today worldwide. They are primarily used for research and training students. Some TRIGA research areas include: irradiating electronic circuits to see how much radiation it takes to impair their functions, developing new and different strains of plant life, fighting cancerous growths, and studying reactor kinetics.

TRIGAs have an amazing prompt negative temperature coefficient. This is an inherent characteristic of the fuel. The fuel is zirconium-hydride and uranium alloy enriched to about 20 percent U^{235}. This alloy is fabricated into the shape of a fuel rod with the zirconium-hydride serving the function of a moderator. Because the fuel and moderator are alloyed, it is somewhat homogeneous and, therefore, any rise in temperature is shared by the uranium and zirconium-hydride simultaneously. This causes the zirconium-hydride to be less effective as a moderator causing more neutrons to stay out of the thermal range resulting in fissions. This shuts the reactor down in just a few thousandths of a second without using control rods. This feature allows the reactor to be pulsed or have a quick increase in power without any danger.

The TRIGA core is immersed in a pool of water. No loss of coolant accident can occur and it uses natural convection to cool the core (no need for pumps). The pool also serves as a shield. It is possible to stand beside the

pool during reactor operation and watch the fuel glow from Cerenkov radiation. Cerenkov radiation is the result of a charged particle moving faster than the speed of light in a particular medium. (Nothing travels faster than the speed of light in a vacuum.) These safety features make TRIGA reactors ideal for operation by students and personnel who have had minimum experience and training.

TRIGAs are like PWRs in that they have cores configured into arrays with fuel and control rods arranged into certain lattice positions. They have different functional sizes. TRIGA's steady-state power ranges from about 10 kW to about 14 MW thermal. TRIGAs are designed to operate both above ground or underground. TRIGAs can be constructed quickly and are inherently very safe.

CONCLUSIONS

It is easy to see that there are many different reactor designs. Their safety and versatility is unmatched. Economically, a nuclear power plant has its biggest advantage in the fuel cost. There are many ways to configure fertile and fissile material into a nuclear reactor. However, commercial power plants in the United States are primarily U^{235} fueled with a thermalized concept.

Thermalizing a neutron is a process whereby a high energy neutron loses its energy through collisions with atomic nuclei. This enhances the probability of a neutron fission event with U^{235}. This process is also referred to as moderation. Materials with low mass numbers make better moderators. Because of similar neutron attenuating characteristics, moderating materials sometimes serve as reflectors. Reflectors help to keep neutrons from leaking out of a reactor by scattering neutrons back into the core.

Shielding materials are used to attenuate gamma and neutron radiation. It is paramount to shield radiation so it does not harm humans, and it is also necessary to shield electronic hardware. Because of different interactions with matter between neutrons and gamma rays, layered shields of different materials are sometimes used. Tailoring the shield to the dose constraints that are safe to humans and electronic hardware is the major shield design criterion.

Fuel for thermal reactors is primarily U^{235}. The U^{235} is enriched to yield better fuel economy. Enrichment can be achieved in different ways. Gaseous diffusion is one method used in the United States. After a desired enrichment of the fuel is obtained, the fuel is fabricated. Cladding is put around the fuel to protect and strengthen it. The coolant used in reactors often determines the cladding material used. Water-cooled reactors usually use zirconium or its alloys, while gas-cooled reactors often use a ceramic cladding material.

Control rods are used to control the power output of the reactor. Boron carbide (B_4C) is a common neutron absorbing material which controls reactivity. Chemical shim is also used in PWRs to control slower charges in power. Boric acid is a common chemical shim material. Sometimes reactors have an inherent safety feature called the negative temperature coefficient. The

reactor temperature affects the reactivity adding more safety in reactor operation. A reactor is said to be critical if its multiplication factor, k, is equal to one. It is supercritical if k is greater than one and subcritical if k is less than one. The value of k is set through the manipulation of the reactor's control mechanisms.

There are several reactor types. PWRs are thermal and are characterized by pressurizing the water coolant. PWRs are safe, versatile in their functional sizes, and they have proven technology.

HTGRs use gas as a coolant. The German reactor, the AVR, uses a pebble bed concept. The fuel is stacked in spheres in the core with helium gas flowing through them. The AVR has achieved the highest outlet temperature ever--950°C. It also has a large negative temperature coefficient and it will go subcritical if the coolant flow is stopped and the control rods are pulled out.

A Peach Bottom core design is another HTGR design. This design is featured by the fuel pin's ability to purge itself of fission products by allowing a small amount of helium gas into the pin and filtering the fission product gases in an internal trap. The less volatile gases are directed to an external trap.

A CNSG is a modified PWR. The distinguishing feature is that it has the steam generating system in the pressure vessel. Its design uses natural circulation, eliminating some pumps. This reactor design powers the ship, "Otto Hahn." The CNSG has not been demonstrated as a power source as much as conventional PWRs.

TRIGA reactors are relatively small swimming pool reactors that can be operated with minimum training. They have a prompt negative temperature coefficient which is caused by the 20 percent enriched U^{235} zirconium-hydride fuel. TRIGAs can be used above and underground.

Reactors put underground offer more security from terrorist and foreign attacks than conventional terrestrial reactors. Problems with deep basing are space constraints, personnel exposure to radiation, and heat rejection. However, these problems are solvable with extra cost. The added security may well be worth the extra cost to ensure a more reliable power source in an emergency situation.

Nuclear power plants have proven reliability, safety records, and versatility. Because of the fuel, nuclear reactors usually pay for themselves faster than conventional power sources. They have provided safe generation of electricity for many years, and they can continue to do this for many more years to come.

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